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On the integration of the CAx systems towards sustainable production

Konstantinos Salonitis[a]*, Panagiotis Stavropoulos[b]

[a]*Manufacturing and Materials Department, Cranfield University, MK43 0AL, UK*
[b]*Laboratory for Manufacturing Systems & Automation, Dept. of Mechanical Engineering & Aeronautics, Patras, Greece*
* Corresponding author. Tel.: +44-1234-758347; fax: +44-1234-751172. *E-mail address*: k.salonitis@cranfield.ac.uk.

Abstract

Achieving sustainable development and succeeding in sustainable production requires changes in industrial processes, type and quantity of resources used, treatment of waste, control of emissions, and finally in the final products. This paper describes a methodology of integrating CAD/CAPP/CAM systems, aiming at the development of methods and models for addressing the challenges arising within the process-planning phase and contributing to the continuous improvement initiatives within the production and manufacturing systems. The ultimate goal of such integration is to assess alternative process plans in different levels, through which, the utilization of the various available resources (such as hardware, personnel and even subcontractors) and their optimal setup can contribute in the overall sustainability of the production facilities.

Keywords: Sustainability; PLM; CAx; Process planning

1. Introduction

The problem of integrated process planning has always been of major importance for the industry. From the early eighties the effort has been focused in reducing the time and cost of the ramp up stage of a new product. Over the last 10 years, a significant number of software tools has been developed focusing on Computer-Aided Design and Process Planning, Computer Aided Manufacturing and Production Planning and Control. Although the issue of the integration and cooperation of all these systems has been thoroughly investigated, even today, in practice all this systems work independently. As a result, slight changes in the design of the product may result subsequently in time-consuming series of loops of life cycle developments.

Taking into consideration that almost 80% of the manufacturing costs are generated in the production preparation stage, especially in the product design stage [1], it is evident that the focus should be on the preparation phase of production and specifically on the process planning. Few studies have been presented on the development of alternative process plans [1]-[3], with their basic approach focusing:

- on the own resources of the production system, neglecting in most cases the potential collaboration alternatives with the subcontractors
- on the production phases as subsequent stages of processing, without considering the technological parameters of the processes incorporated in each phase, and the different market needs during the life cycle of the product.

Furthermore, the theoretical models and software systems developed for the construction of alternative process plans present a high degree of complexity and require a vast amount of highly accurate input data, prohibiting their adoption from SMEs. So the current industrial practice on the construction of process plans is mostly empirical, taking into consideration only basic data for the market orders and the quality characteristics of the products to be produced. Thus the process plans that are delivered are in general inflexible and cannot take into consideration alternative market demand profiles.

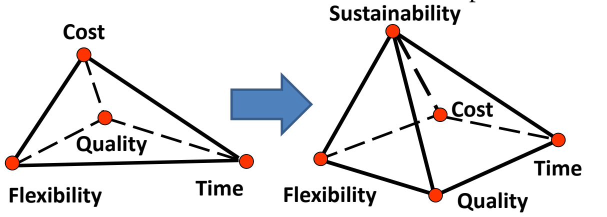

Fig. 1. Manufacturing decision-making attributes evolution

At the same time there is a need to move towards more sustainable design and production means. Sustainability term has been used to indicate the need for the society to live within its means and use energy and materials in a way that will not compromise the standards and health of future generations [4]. As such, the reconciliation of environmental, social and economic demands is required (i.e. the triple bottom line). This reconciliation cannot be realized without more efficient approaches and technologies, which must in part be provided by manufacturing.

Manufacturing companies have recognized the need for change and a number of methods have been derived for improving their performance and move towards more sustainable practices. Indicatively, the helix of sustainability [5] is a concept based on mapping models of raw material use and reuse onto those of nature.

However, these methods are coping with sustainability in isolation to the established metrics for assessing the manufacturing performance. Traditionally monitoring four main classes of manufacturing attributes; namely cost, time, quality and flexibility assesses the performance of a manufacturing system.

These four attributes do not take into consideration energy or resources efficiency that are key factors to sustainability. It is evident that the manufacturing decision tetrahedron that was proposed by Chryssolouris [6] has to be extended as to include "sustainability" as a new driver in manufacturing (Figure 1).

Sustainability relies on considering the product's entire lifecycle during the planning stage. The design of sustainable products is therefore affected by a number of factors such as: raw materials, supply chain considerations, manufacturing operations, usage, service and decommissioning.

On the other hand sustainable production relies on the environmental friendliness of production plants and manufacturing processes. This is assessed in a number of ways, indicatively through energy consumption, water consumption, waste and emissions, health and safety of its workers, etc. Another challenging aspect is the sustainable performance of the whole supply chain and not only the manufacturer itself.

It is evident that success in creating sustainable products through sustainable manufacturing processes requires understanding and effective lifecycle management. Product life cycle management (PLM) systems are the basis for managing the entire lifecycle of products from conception to final disposal. In general three phases exist within the product's lifecycle, the beginning of life (BoL), the middle of life (MoL) and end of life (EoL) [7]. In conventional PLM systems, only BoL is considered. However aiming towards sustainability, the conventional PLM systems have to be enlarged and consider MoL and EoL phases as well [8]. However, a number of challenges prohibit the complete integration, including [7] –[11]:

- integration of different software tools (such as CAD, CAM, CAE, CAPP in the BoL phase with MRP, ERP, SCM in the MoL) under one platform
- interoperability of systems and devices (a lot of different devices such as technical systems, management systems, smart devices etc. to be integrated) both internally and externally of the organization
- spectrum of standards used within the CAx systems (for example STEP, SysML, PSL, PLCS, ebXML etc.)
- amount, archiving and sharing of data between the various phases of the lifecycle

2. Designing sustainable products

Allwood and Cullen [12] highlighted the effect of component's weight on sustainability. Lightweight design has been proven to be more sustainable due to the more efficient use of raw material; reduction of scrap, and for the case of moving parts requires less energy during operation. Typical applications that their design is optimized with regards their weight is found mainly in the aerospace industry. On the other hand though, engineering community, since the beginning of 1900s, strive for standardization as to take advantage of economies of scale related to tooling costs and the speed of continuous processes. Such standardization however results in simple designs with parts being heavier than the optimized ones. Allwood and Cullen [12] came up with five design principles for using fewer raw materials that should be considered for sustainable design. Ijomah et al. [13] on the other hand presented a set of guidelines for remanufacturing to further enhance sustainable manufacturing. Another significant aspect when designing sustainable products has to do with ensuring that regulatory requirements, energy power goals, manufacturability, serviceability and end-of-life considerations are met.

3. Sustainable Production

Sustainable production and manufacturing implies that the processes and practices used for producing products meet the requirements for all three pillars of sustainability. Since there is no universally accepted definition for sustainable production, a recent study describes it as a process that leads to: (i) improved environmental friendliness, (ii) reduced cost, (iii) reduced power consumption, (iv) reduced wastes, (v) enhanced operational safety, and (vi) improved personnel health [14]. Production facilities have to address a constantly increasing demand for consumer goods since living standards are on the rise.

Reducing energy consumption, while increasing the usage of renewable energy, is crucial as nearly one third of global energy demand and CO_2 emissions is attributable to production activities. This also requires consideration of the factory-level and the exploitation of innovative energy-efficient actuators and components to their full extent while also considering the entire supply chain, from raw material manufacturing stages up to the final component production. Process monitoring and control can provide support, for optimising the performance and resource consumption on machine, factory and supply chain level, where decision support systems consider energy consumption globally. This includes selectively switching off systems and components, using smart sensor networks and energy-efficient scheduling approaches, reducing peaks in energy demand, recovering and reusing electrical energy from decelerating drives or process heat, etc. Process monitoring should also support the consideration of resource-efficiency in maintenance approaches.

At process level there is a need to achieve optimized technological improvements for reducing energy and resource consumptions, toxic wastes, occupational hazards, etc., and for improving product life by manipulating process-induced surface integrity.

Sustainable production can be achieved from using more energy efficient processes. As an example, a lot of research is ongoing in substituting conventional processes that exhibit high energy consumption with novel hybrid ones. Indicatively, grind-hardening process is considered as an alternative to conventional heat treatment for small lot sizes [15] - [17].

As stated, the term sustainability has become synonymous with not only the preservation of the environment, but importantly cost savings and efficiency. Discrete Event Simulation (DES) is a powerful technique for understanding the behavior of systems.

4. Life cycle considerations

The life of products is quite variable. Ranging from few minutes for the case of metal cans to more than 30 years for the case of airplanes and even 100s of years for buildings and infrastructures. Prolonging the life of the products subsequently reduces the demand for new material and reduces the environmental impact of production. Additionally, reusing or even refurbishing the parts before recycling and discarding can further decrease energy demand and environmental impact.

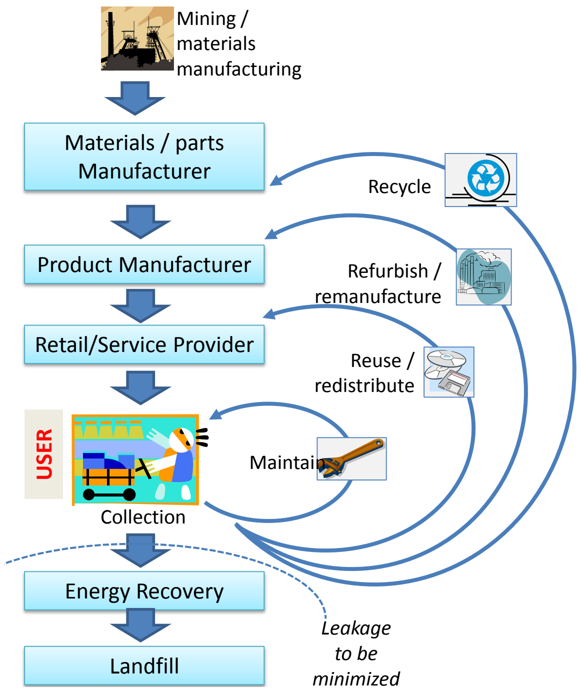

Fig. 2. Circular economy – only technical materials represented. For both biological and technical materials, the reader could refer to [18]

Based on this prolonging idea, an interesting initiative from Ellen Macarthur foundation [18] with regards the life cycle of manufactured parts suggests the transition from "linear to circular economy". A circular economy seeks to rebuild capital, whether this is financial, manufactured, human, social or natural. The basic idea is to replace a linear industrial model with one based around re-use and recycling. This ensures enhanced flows of goods and services. In figure 2 the circular economy concept for technical materials is presented. Some of the loops involved in a circular economy are shown, indicating how products are designed to be fixable, refurbishable, and recyclable at the end of their lifetimes – "an industrial system that is restorative by design". The most sustainable design is the one that lies in the most internal loop.

A common tool used for assessing the environmental impact of a product during its life for cradle-to-grave is life cycle assessment (LCA). LCA is used for assessing stressors (CO_2, CO, NOx, SOx, particulates, toxic waste) over the entire life. This impact is summarized into an "eco-indicator" factor. However, for conducting a full LCA a lot of time and resources have to be invested, and even then the results are subject to uncertainty. However, since 80% of environmental cost determined at design stage when many decisions still fluid, LCA can be used for identifying which phase dominates, for example in the case of civil aircrafts almost 95% of the energy is consumed during the use of the product, whereas for the case of furniture most of the energy is consumed during the manufacturing phase.

One approach to improve sustainability in production is combining DES and LCA, to analyze how changing production parameters affect the waste materials and energy used by the system along with the throughput. Indicatively, Johansson et al. [19] describe how DES could be utilized in combination with LCA for decreasing environmental impacts during food production while Johansson et al. [20] used a model of a paint shop to demonstrate planning a manufacturing setup with an emphasis on sustainability. Common platform of aforementioned studies is the development of a proactive tool, to analyze the cause-effect of current production practices and to investigate alternative practices. Integration of DES and LCA analyze the utilization and processing of production resources in a factory setting. On an economic aspect such method can significantly reduce the financial and environmental costs by evaluating the system performance before its construction or use.

5. Methodology – Research approach

Taking into consideration the state of the art, the research approach aims at the development of a simple, nonetheless effective, method that enable the process engineer to issue a generic process plan able to adapt to all possible different scenarios of market needs and assess them with regards their sustainability. Therefore, it will be possible to reveal shortcomings in the design of the product and assess alternative approaches for the production of the product (such as use of alternative equipment, resources, or even subcontracting). These process plans have to be assessed with regards their environment, social and economic aspects in all phases of the lifecycle.

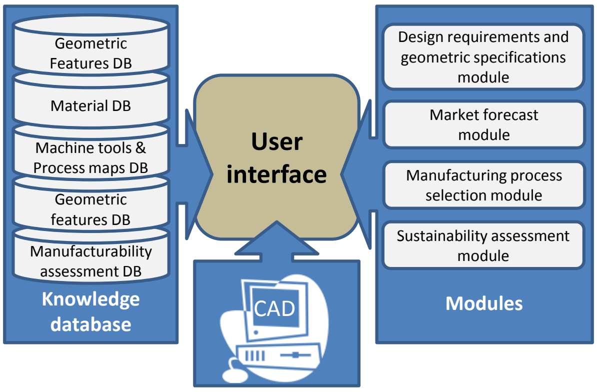

Fig. 3. Architecture of the proposed integrated CAx system

6. Framework for an integrated CAx system towards sustainability

The basic goal is to provide a number of alternative process maps during the concept generation in order to promote accurate decisions. The system proposed, at its operational form, will be composed by a number of modules, interfaces and knowledge databases. The overall architecture of the currently implemented system illustrated in Figure 3, followed by a detailed description of the modules.

Design requirements and geometric specifications module

Within the first module a number of parameters are defined based on the specifications and requirements. These values can include product cost, manufacturing time, machine utilization, product quality, production volume, product weight, and material strength. In this module, the component features information from CAD files are specified into a geometric feature database. This information includes feature name, shape, length, and width.

Market forecast module

This module will take into consideration the parameters related to the market requirements during the industrialization, i.e. the actual production of the product. The objective of these models is to assess the market status and to identify different market profiles that may emerge during the product lifecycle. These models can be integrated in a series of algorithms allowing for the identification of possible alternative resources, which could be used for the production of parts or the product itself, fulfilling the order requirements, including the quality specifications of each lot of the order. The resources under investigation can include own resources of the production system, the forecasted ones that may be acquired (purchase or leasing) and the available subcontractors' resources.

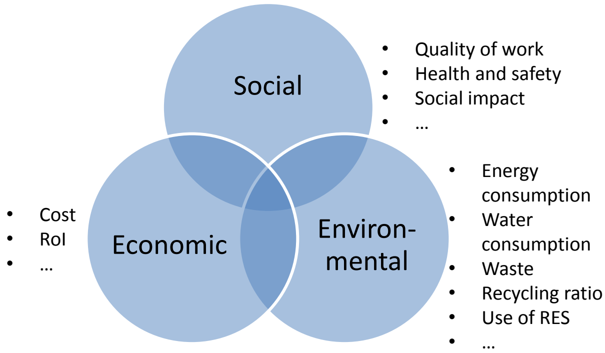

Fig. 4. Representation of the components that compose the proposed methodology

Manufacturing process selection module

After determination of the specifications, designers provide manufacturing processes information. This is an important element of the system, as in general more than one manufacturing processes can be suited for a specific part/assembly. The selection of the most suitable manufacturing processes can be accomplished through the four manufacturing attributes: cost, time, flexibility and quality. Key performance indicators (KPIs) are well established for each one of these manufacturing attributes. “Cost” incorporates a number of factors such as equipment and facility costs, material cost, labour, overhead etc. On the other hand, “time” attribute is monitored using KPIs such as “throughput time”, “cycle time”, “lead time” etc. In a similar way “quality” is assessed through “surface roughness” measurements, “cost of quality”, etc.

Sustainability assessment module

The major KPIs that are used for assessing the sustainability of the proposed solution are shown in Figure 4.

Energy efficiency can be used as a key sustainability indicator, as it is related to all three bottom line aspects. However the existing definitions of energy efficiency can be rather misleading as indicated by Bunse et al. [21]. In general “energy efficiency” refers to technologies and standard operating procedures that reduce the volume of energy per unit of industrial production. A number of energy related KPIs have been introduced and can be categorized into metrics focusing in the energy consumption (such as energy consumed per product, total on-site energy, total energy use etc.), environmental impact (CO_2 emissions, greenhouse gas emissions, etc.), financial figures (e.g. energy cost), focusing on the process level, machine tool or production plant etc.

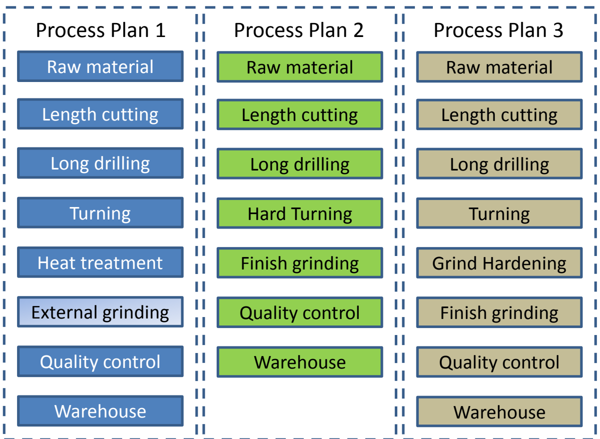

Fig. 5. Validation scenario

7. Method validation

A simplified version of the proposed system was developed within Microsoft Excel coupled with Microsoft Access databases. A case study of a simple geometry part (shaft) requiring a number of processes was used as a case study validation. The simple part can be manufactured in a number of different ways and following different manufacturing routes as can be seen in Figure 5.

A matrix for communicating alternatives was developed to select the appropriate process plan (Table 1). For the criteria that can be compared with pre-specified targeted values (such as cost or CO_2 emissions), specific symbols were used. It is clear from Table 1 that no one process plan can be selected at first look, and this would be even more difficult for a more complicated part, or if different raw materials were considered. In order to narrow down the solution and to select the appropriate process plan, radar diagrams can be used. Figures 6 and 7 present these diagrams for two different demand scenarios; low and high demand respectively. The overall performance of each process plan can be quantified through the area covered in the “radar” diagram. Figure 8 compares this index for these process plans under three different market demand values.

Table 1. Matrix for communicating alternatives (low demand)

	Process plan 1	Process plan 2	Process plan 3
Energy efficiency	+	+++	++
Raw material efficiency	++	++	++
Waste management	+	++	++
CO2 emissions	+	+++	++
H&S of workers	+	++	++
Work Quality	+	++	++
Use of RES	++	++	++
Cost efficiency	+	++	++
Energy efficiency	+	+++	++

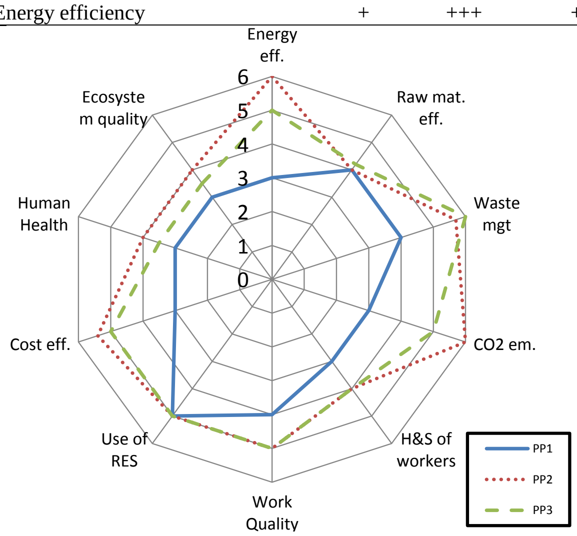

Fig. 6. Assessment of the three process plans for low demand

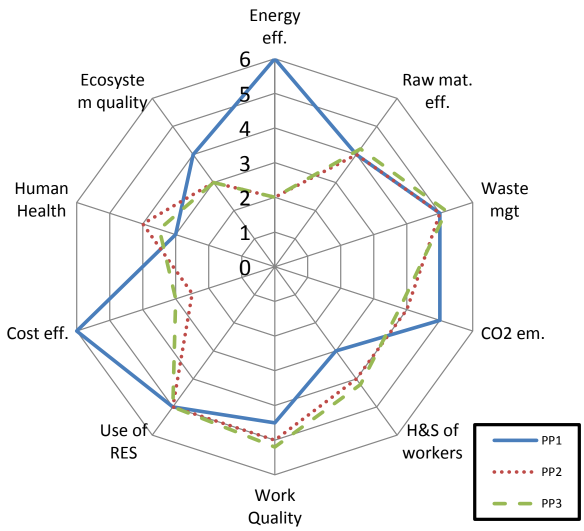

Fig. 7. Assessment of the three process plans for high demand

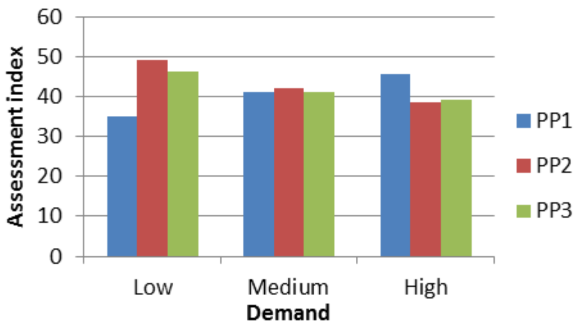

Fig. 8. Overall assessment of the three process plans

By comparing assessment results it is obvious that no ideal process plan exists. Depending on the demand level, a process plan can become a better solution than another. This highlights the need for precise and accurate forecast models.

8. Conclusions

The paper presents and discusses the need for integrating CAx tools in order to address the challenges arising within the process-planning phase and contributing to the continuous improvement initiatives within the production and manufacturing systems. A simplified method for assessing the sustainability of different process plans was presented and validated.

The potential for future developments exists and a number of topics have been identified such as to include a material selection module to be coupled with the Cambridge Engineering Selector software. Additionally the developed tool could be coupled with a CAD system and thus simplifying the procedure for entering the geometric features.

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